Research Report

TEMPORAL OSCILLATIONS IN HUMAN PERCEPTION

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Abstract—*The notion that human perceptual decisions are based on discrete processing cycles rather than a continuous accumulation of information was examined experimentally. Significant periodicities were found in human response times (RT) to feature and conjunction discrimination tasks in the visual and auditory modalities. Individual RT histograms were multimodal, with regularly spaced peaks and troughs, indicating that responses were emitted more frequently at regularly recurring time intervals following stimulus presentation. On average, responses were initiated after four to seven discrete processing steps whose "quantum" duration was proportional to task difficulty.*

Measurement of human response times (RT) is a widespread technique in cognitive psychology (Luce, 1986; Posner, 1978). It is commonly assumed that mental processing time has a large stochastic component and may vary continuously, on a millisecond scale, as a function of stimulus characteristics and task demands (Luce, 1986). Psychological models postulate a series of consecutive processing stages (Donders, 1969; Sternberg, 1969), each with variable duration. RT, which is the sum of these durations, is therefore expected to be broadly distributed, and in general only its mean or median is considered significant.

A number of authors have considered the alternative possibility of a temporal quantification in mental processing. Stroud (1955) proposed the "perceptual moment hypothesis," according to which perceptual inputs are chunked into discrete temporal intervals according to the regular oscillations of a "central intermittence." Since then, data suggestive of an "internal clock" or subjective "time quanta" have been reported occasionally (Allport, 1968; Augenstine, 1955; Collyer, Broadbent, & Church, 1992; Harter & White, 1968; Jokeit, 1990; Kristofferson, 1967a, 1967b, 1980; Latour, 1967; Michon, 1967; Pöppel, 1970; Shallice, 1964; M. Treisman, Faulkner, Naish, & Brogan, 1990; M. Treisman, Faulkner, & Naish, 1992). Several of these studies have reported multiple discrete peaks in histograms of a few hundred reaction times or ocular movement times. The observed periodicities have sometimes been tentatively linked to physiological events, such as the alpha rhythm of the electroencephalogram (Callaway & Yeager, 1960; Kristofferson, 1967a, 1967b; Latour, 1967).

Most of those data were collected before computer facilities existed, and their statistical reliability has been criticized severely (Vorberg & Schwarz, 1987; Vroon, 1970, 1974). However, more recently, electrophysiological recordings from auditory and visual brain areas have revealed stimulus-dependent oscillations in the range of 30 to 80 Hz (Basar-Eroglu & Basar, 1991; Eckhorn et al., 1988; Engel, König, Kreiter, & Singer, 1991; Engel, Kreiter, König, & Singer, 1991; Engel, König, & Singer, 1991; Galambos, Makeig, & Talmachoff, 1981; Gray, König, Engel, & Singer, 1989; Gray & Singer, 1989; Pantev et al., 1991; Ribary et al., 1991). These results have again suggested that the neuronal encoding of sensory information may be discrete in time.

The present study investigated whether a temporal periodicity or discreteness might be perceptible in individual subjects' distributions of RTs during perceptual discrimination tasks. To this end, 1,600 RTs were collected from each of five highly trained observers in each of four two-choice tasks. It was reasoned that the period or phase of the putative oscillatory processes might differ between subjects or between tasks, thereby hindering any meaningful analysis of composite data sets. The experimental design and the statistical analyses therefore focused on studying RT distributions from single subjects performing a fixed task.

Four tasks were used to explore systematically the effect of two variables, stimulus modality and attention, that previous work suggested might affect internal oscillatory processes. First, stimulus modality was manipulated by contrasting two tasks of auditory discrimination with two tasks of visual discrimination. Electro- and magnetoencephalographic recordings of 40-Hz oscillations in humans have mainly used auditory stimuli (Galambos et al., 1981; Pantev et al., 1991; Ribary et al., 1991), whereas most related electrophysiological experiments in animals have used simple visual stimuli (Eckhorn et al., 1988; Engel, König, Kreiter, & Singer, 1991; Engel, König, & Singer, 1991; Engel, Kreiter, et al., 1991; Gray & Singer, 1989; Gray et al., 1989). It was therefore of interest to examine the presence of periodicities in RTs to stimuli in both modalities. Second, attention and task difficulty were manipulated by contrasting, in each modality, simple feature discrimination tasks with more complex conjunction discrimination tasks. The feature tasks required simple discrimination along one stimulus dimension: orientation for visual stimuli and pitch for auditory stimuli. The more difficult conjunction tasks required identification of a spatial or temporal relation between the same elementary features. Several authors have theorized that temporal oscillations may play a role in attentive feature binding (Crick & Koch, 1990; Eckhorn et al., 1988; Engel, König, Kreiter, & Singer, 1991; Engel, König, & Singer, 1991; Engel, Kreiter, et al., 1991; Gray & Singer, 1989; Gray et al., 1989; Sporns, Tononi, & Edelman, 1991; von der Malsburg & Schneider, 1986; see also Damasio, 1989). If this hypothesis is correct, then oscillations might be found only in the conjunction tasks, but not in the more simple feature tasks.

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METHOD

Design and Stimuli

In order to examine the distributions of individual subjects' RTs, 1,600 RTs were collected from each of five observers in each of four tasks: visual feature (VF), visual conjunction (VC), auditory feature (AF), and auditory conjunction (AC). In each task, one of two alternative stimuli was presented on each trial, and the subject had to respond as fast as possible by pressing a corresponding right-hand or left-hand Morse key. The stimuli were as follows:

- *Visual feature task:* vertical versus horizontal 7-mm bars, centered on a computer screen (bright orange against a black background), subtending approximately 50° of visual angle from a viewing distance of about 50 cm.
- *Visual conjunction task:* letters *T* and *L* made up of two such 7-mm bars. The stimuli were centered and randomly oriented at 0°, 90°, 180°, or 270° from upright and therefore differed only in the spatial disposition of their component lines.
- *Auditory feature task:* computer-generated square-wave sounds of 100 ms duration, with a pitch of 440 Hz (A) or 1,245 Hz (D#). The stimuli were generated on-line via the computer's internal loudspeaker, with an intensity of 60 dB.
- *Auditory conjunction task:* sequences of the same tones, shortened to 50 ms duration, with two possible orders (A–D# vs. D#–A).

On each task, total stimulus duration was 100 ms, and the response-to-stimulus interval was 1,300 ms. Stimulus presentation and RT measurement were controlled with IBM-compatible portable computers. Visual presentation was synchronized with the 60-Hz refresh cycle of the plasma screen. Each task comprised 1,600 trials split into eight consecutive sessions of 200 trials each, with an equal number of the two target stimuli within each session. No precise control was imposed concerning the time of day at which the experiment was run. The eight sessions were generally run over a few consecutive days, with two to four sessions per day.

Subjects

Five observers with considerable experience in RT tasks, including the author, served as subjects. In order to control for possible hardware-induced periodicities, different computers were assigned to different subjects, and the computers' internal timers were programmed to a 1-ms accuracy using two different software methods.[1] Observers S.D. (male, age 26) and G.D. (female, age 31) passed the experiments using Timing Method 1 on a Toshiba T-5100, in matched order (AF, AC, VC, VF for S.D.; AC, AF, VF, VC for G.D.); observers C.P. (male, age 23) and P.G. (male, age 22) passed the experiments using Timing Method 2 on a Toshiba T-5200, in matched order (AC, AF, VF, VC for C.P.; AF, AC, VC, VF for P.G.); and observer A.C. (female, age 24) used Timing Method 1 on a Toshiba T-2100 (order AC, AF, VC, VF).

RESULTS

Identification of a Periodicity

I first detail the statistical identification of oscillations for observer G.D. in the visual conjunction task. G.D.'s 1,462 correct RTs were pooled across the eight sessions and across the different stimulus–response conditions. Histograms were then plotted using a bin size of either 1 ms (Fig. 1a) or 6 ms (Fig. 1b).[2] Visual inspection of the 6-ms histogram revealed a regular pattern of peaks and troughs. The interval between peaks was approximately stable at 30 ms. An autocorrelogram of the 6-ms histogram after high-pass filtering at 20 Hz confirmed the presence of rhythmicity (Fig. 1c). To measure the oscillation frequency, a fast Fourier transform (FFT) was performed on the millisecond-by-millisecond histogram, using a 256-ms window centered on the median RT. Over the interval from 20 to 100 Hz,[3] the periodogram showed a large coefficient at 35.2 Hz, corresponding to an oscillation period of 28.4 ms (Fig. 1d).

Significance Tests

Sampling from a unimodal distribution is likely to yield a histogram with multiple peaks, especially when the number of samples is small. Chance alone might explain the regular spacing of these spurious peaks, thus mimicking a periodic process. I therefore used a nonparametric Monte-Carlo method to evaluate, separately for each individual distribution, the null hypothesis that the observed peaks were due only to finite sampling from a smooth, nonoscillatory distribution. The millisecond-by-millisecond histogram of *n* correct RTs was low-pass filtered at 20 Hz (Fig. 1a) and then used for the computer generation of 10,000 sets of *n* simulated RTs. Each of these 10,000 control sets was then treated in the same way as the original data. An RT histogram was tabulated, and an FFT was used to quantify the presence of periodicities. This method yielded an evaluation of the expected range of FFT coefficients when the underlying distribution was known to

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[1] Both methods involved reprogramming counter 0 of the 8254 chip, present in IBM-compatible AT computers, that normally sends an interrupt 08 to the microprocessor every 54.9 ms. In Timing Method 1, the 8254 chip was reprogrammed to send an interrupt every millisecond, and this interrupt was used to increment the RT counter. In Timing Method 2, the 8254 chip was reprogrammed to allow access to an internal register that decremented continuously at a rate of 1.193 MHz. The accuracy of this second timer was below 0.2 ms. The accuracy and lack of bias of both timers were checked with signals of known accuracy.

[2] Histograms with a bin size of 6 ms and the corresponding cross-correlograms were used only for illustration. All statistical analyses were based on the raw data gathered into millisecond-by-millisecond histograms. The present method does not require the selection of an arbitrary bin-size parameter (Pöppel, 1970; Vorberg & Schwarz, 1987).

[3] With the present technique, only frequencies in this interval could be studied reliably. Frequencies below 20 Hz were contaminated by the slow rise and fall of RT distributions, whereas frequencies above 100 Hz were masked by the minimum intrinsic variance of RTs, which is approximately 30 to 50 ms^2 (Hopkins, 1984; Hopkins & Kristofferson, 1980).

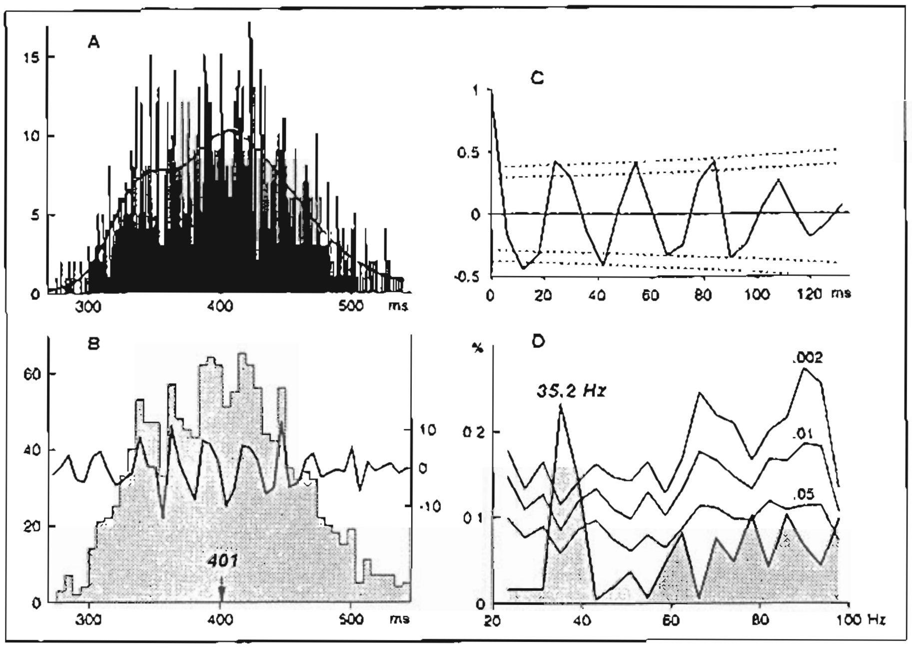

Fig. 1. Evidence for oscillations in the distribution of response times (RTs) from observer G.D. in the visual conjunction task. (a) 1-ms histogram of G.D.'s 1,462 correct RTs. The ordinate is the number of observations per bin. The smooth curve is the histogram after low-pass filtering at 20 Hz, used for the generation of control, random data sets. (b) 6-ms histogram of the same data. The arrow indicates the median RT. The curve is the histogram after high-pass filtering at 20 Hz, showing a clear oscillation around 35 Hz. (c) Autocorrelogram of the curve in (b). Dotted lines show the values of the correlation coefficients that were significant at the .01 and .001 levels. (d) Periodogram based on a fast Fourier transform (FFT) of the 1-ms histogram, using a 256-ms window centered on the median RT. Significance levels were computed for each Fourier coefficient by drawing 10,000 control sets of 1,462 simulated RTs from a random-number generator using the smooth distribution in (a). An FFT was performed on each set, and the 10,000 Fourier coefficients at each frequency in the range from 20 to 100 Hz were sorted in decreasing order. Horizontal curves show the value of the 20th, 100th, and 500th coefficient for each frequency, corresponding to significance levels of .002, .01, and .05 before Bonferroni's correction.

be nonoscillatory, but otherwise extremely similar to the actual data. For observer G.D. in the visual conjunction task, none of the 10,000 simulated data sets had a Fourier coefficient larger than the peak at 35.2 Hz in the original data (Fig. 1d). Since 20 frequencies are tested in the interval from 20 to 100 Hz, the level of significance of the peak is $p < .002$ with Bonferroni's correction. One may therefore reject the hypothesis that the observed oscillation was a chance event.

In principle, statistical methods based on FFTs and autocorrelograms are appropriate only with data from stationary time series. However, calculating the Fourier transform of an RT distribution is (although computationally more efficient) mathematically equivalent to calculating the polar quantogram of the original set of RTs, a classical statistical method for assessing the presence of quanta (Kendall, 1988). In addition, two controls were performed in order to verify that the nonstationary aspects of RT distributions were not, by themselves, responsible for the observed periodicity. The same analysis was run, first, on a narrower temporal range over which the distribution appeared fairly stationary (e.g., from 330 to 470 ms in Fig. 1a) and, second, after differencing the data (i.e., applying the FFT to $d_{i+1} - d_i$ instead of the original distribution d_i). In the case of G.D.'s data, both analyses confirmed the existence of a periodicity at 35.2 Hz ($p < .002$ with Bonferroni's correction). Similar consistency checking was successfully performed with the other data sets and is not detailed any further. The FFT was also supplemented with a maximum entropy method of spectral estimation, which yielded similar results.

Differences Across the Four Tasks

Table 1 gives the value and significance of the highest spectral peak uncovered in each of the 20 data sets (5 observers × 4 tasks). A significant periodicity was found in 14 out of 20 data sets, and with at least 3 out of 5 observers in each task. Different observers tested with the same apparatus sometimes showed substantially different oscillation periods, and compiling their data into a single histogram generally suppressed all periodicities, thereby excluding the possibility of a hardware artifact. Across tasks, the oscillation period varied from 10.2 to 36.6 ms. A two-way analysis of variance indicated that the period was systematically longer in conjunction tasks than in feature tasks, $F(1, 4) = 34.9$, $p < .005$, and that this effect was more pronounced in the auditory modality than in the visual modality, interaction $F(1, 4) = 20.9$, $p < .02$. On individual t tests, the period was significantly longer in the auditory conjunction task than in the other three tasks ($p < .02$), which did not differ significantly from one another.

Median RT varied in parallel with the measured period. RT was longer in conjunction tasks than in feature tasks, $F(1, 4) = 81.9$, $p < .001$, and this effect was again more pronounced in the auditory modality than in the visual modality, interaction $F(1, 4) = 12.2$, $p = .025$, although it reached significance in both modalities ($p < .05$). A regression analysis showed that median RT was linearly related to the oscillation period T according to the equation $RT = 225 + 5.53\ T$, $r^2 = 65.3\%$, $p < .0001$ (see Fig. 2). Similar correlations were found with the upper and lower quartiles of the RT distributions, respectively, $RT(25\%) = 209 + 4.73\ T$ and $RT(75\%) = 237 + 6.65\ T$ (both $ps < .0005$).

DISCUSSION

The present data prompt a reappraisal of the notion that human perceptual and decision processes are quantified

Table 1. *Oscillation frequency (Hz) for five observers in the four discrimination tasks*

	Task			
Observer	Auditory feature	Auditory conjunction	Visual feature	Visual conjunction
S.D.	85.9	46.9**	82.0^{+}	66.4**
G.D.	74.2**	27.3**	70.3	35.2**
A.C.	97.7*	35.2**	50.8^{+}	46.9
C.P.	74.2^{++}	27.3**	70.3*	66.4
P.G.	85.9	27.3^{++}	58.6	54.7*
Average	83.6	32.8	66.4	53.9
Mean RT (ms)	278	407	312	341
Errors (%)	7.7	8.8	11.3	11.8

Note. Frequency = most significant peak of the fast Fourier transform (FFT) periodogram in the range from 20 to 100 Hz. Bonferroni-corrected significance levels: $^{*} = p < .05$; $^{+} = p < .02$; $^{++} = p < .01$; $^{**} = p < .002$. Since the FFT was performed on a 256-ms window over the RT distributions, only 128 estimates of the complex Fourier coefficients were obtained over the Nyquist range from 0 to 500 Hz, or only 20 estimates over the interval from 20 to 100 Hz. Therefore, the periodogram could be calculated only at frequencies that were integer multiples of 500/128 ≈ 3.9 Hz. Hence the identical frequency values in several columns.

(Stroud, 1955). They indicate that on a fine time scale, responses are not distributed randomly with respect to stimulus presentation, but are emitted more frequently at regularly recurring time intervals after the stimulus first appeared.

Several experimenters have previously claimed to have identified periodicities in RT distributions (Augenstine, 1955; Harter & White, 1968; Jokeit, 1990; Latour, 1967; Michon, 1967; Pöppel, 1970; Vroon, 1970). However, these original studies suffered from a number of flaws that may explain why this line of research has remained marginal. First, until recently, it has been impractical to record and analyze several thousand RTs. Even Jokeit's relatively recent article (1990) included only 152 RTs from a single subject. In addition, many authors failed to mention how their data sets were selected, thus leaving open the possibility that periodicities were obtained only from a few subjects in a large study, and might therefore be a chance event. By contrast, the present study included 20 data sets of 1,600 trials each. Although periodicities sometimes seemed visible when analyzing smaller subsets of the data (e.g., right-hand responses or first four sessions only), statistical significance was hardly ever reached when fewer than 1,000 RTs were included in the distributions.

Second, previous studies often resorted to some complex preprocessing of the data in order to demonstrate the presence of periodicities. In some cases, the periodicities appeared to be artifacts of the preprocessing rather than genuine psychological phenomena. For instance, Pöppel (1970) plotted histograms of about 260 RTs, reported the presence of multiple peaks, and evaluated the oscillation period as the mean interpeak interval in a histogram with 10-ms bins. However, Vorberg and Schwarz (1987) demonstrated that this procedure was biased and could "discover" periodicities even in artificial data drawn from a unimodal distribution. Similarly, Jokeit (1990) discovered periodicities in a histogram of the RT differences between any pair among a set of 152 RTs. However, the histogram was both "smoothed and trend-reduced" in an unspecified way before periodicities were at all visible. It seems likely that smoothing, which acts as a low-pass filter, and trend reducing, which is equivalent to a high-pass filter, together contributed to the selective amplification of random fluctuations in a narrow bandwidth, thereby yielding an impression of periodicity.

The present results, by contrast, seem less susceptible to such statistical artifacts. Regularly spaced peaks were often obvious in the raw RT distributions (Fig. 1). In addition, the possibility that sampling and statistical procedures themselves were responsible for the observed oscillations was assessed by systematic comparison to a large number of random data sets drawn from a distribution that was known to be nonperiodic. In 14 out of 20 data sets, periodicities were found more often than could be explained by chance (Table 1).

The present study underlines the psychological significance of periodicities in RT distributions by demonstrating that the oscillation period is systematically related to task difficulty. The observed correlation between median RT and the oscillation period suggests a decomposition of decision time into two components, one of fixed duration and the other showing discrete temporal oscillations. In the regression equation $RT = 225 + 5.53\ T$, the constant of 225 ± 40 ms coincides roughly with the minimal value for simple RTs (Luce, 1986), and can be tentatively ascribed to stimulus transduction and motor response. The regression slope 5.53 ± 1.86 indicates that a response is generally initiated after four to seven processing cycles. This figure remains remarkably constant across variations in task difficulty. Cycle duration, in contrast, varies considerably with task difficulty and is shorter when the task requires simple feature discrimination than when the task implies a conjunction of two different features (A. Treisman & Gelade, 1980). The present results do not appear to support the view that oscillations are present only when the task requires a conjunction or "binding" operation (Crick & Koch, 1990), since fast but significant oscillations were observed in the two simple feature discrimination tasks.

A possible model for the present data, depicted in Figure 3, supposes that perceptual information is not transmitted continually to higher processing stages, but is made available only at regularly recurring time intervals following stimulus presentation. An adequate metaphor is the notion of information packets that are transmitted to subsequent stages of processing only when the perceptual information has been appropriately synthesized and registered. This "packaging" of perceptual information seemingly takes longer when a conjunction of features is required. Finally, for each in-

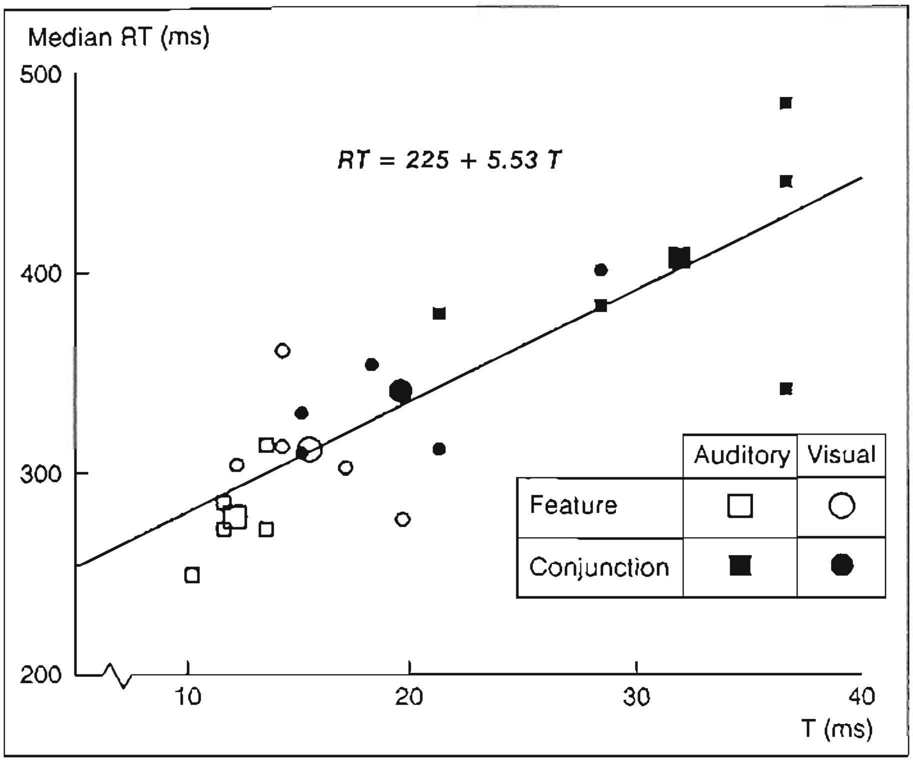

Fig. 2. Correlation between median RT and the oscillation period (*T*). Small symbols show data from individual observers. Large symbols show averages over the five observers.

formation packet reaching the decision stage, either a response is initiated immediately or the decision is postponed to the next cycle, eventually generating multiple discrete peaks in the RT distribution.

This model can be formalized mathematically with five free parameters estimated from the RT distribution: mean and standard deviation of the constant duration before the first peak, mean and standard deviation of the number of cycles before responding, and the duration of the cycle itself. Figure 3 demonstrates the reasonable fit achieved with this model.

The proposed model may help to delineate the assumptions that must be satisfied for periodicities to show up in RT distributions. First, the postulated processing cycles must remain in phase with the onset or offset of the stimulus; otherwise, the peaks and troughs from successive trials would cancel each other. The present data cannot be explained in terms of a central oscillation or internal clock that would run continuously and independently of sensory inputs (Pöppel, 1970). Rather, the phase of the oscillation must be reset on each trial.

A second assumption is that the delay ascribable to sensory transduction and motor response has a low variance. Distinct peaks will appear in the RT distribution only if the interpeak interval, which is the period of the oscillation, is larger than twice the standard deviation of the sensorimotor delay. Hopkins and Kristofferson (1980; Hopkins, 1984) found that trained subjects showed "ultrastable stimulus-response latencies" with a standard deviation as low as 6 to 7 ms. This value suggests that, in theory, oscillations with periods as small as 12 to 14 ms, or frequencies as high as 70 to 85 Hz, could be identified from the RT distributions of trained subjects. Indeed, an average frequency of 83.6 Hz was found in the auditory feature task. It should be noted, however, that subjects were extremely fast in this task (average = 278 ms), and that they therefore responded after only a few oscillation cycles. It seems unlikely that any biological mechanism could maintain a very precise frequency over many cycles. For instance, Jokeit's (1990) finding of a 100-Hz periodicity in a sample of 152 RTs ranging from 650 to 1,200 ms seems implausible, since the 10-ms period would have had to remain stable to within a fraction of a millisecond for more than 60 cycles.

Finally, a third assumption is that the oscillation period and the sensorimotor delay both remain approximately constant throughout the testing sessions. While this assumption seems to hold for the eight consecutive sessions used here, preliminary results suggest that more extensive training can reduce the minimal stimulus-to-response delay, therefore leading to an apparent shift of the oscillation phase. RT oscillations can therefore seemingly disappear if data from too many trials are compiled. With observer S.D., two sets of 1,600 RTs were collected in the auditory conjunction task. The FFT identified a significant oscillation both in Set 1 (46.9 Hz, $p < .002$) and in Set 2 (62.5 Hz, $p = .014$). The cross-correlogram of the 20-Hz through 100-Hz components of the two histograms was oscillatory at about 50 Hz. However, interestingly, the two components were negatively correlated at lag 0, $r = -.321$, $t(254) = 5.40$, $p < 10^{-6}$: The peaks in the first histogram coincided with the troughs of the second. This was accompanied by an acceleration of median RT from 379 to 361 ms.

Such a phase shift with training was replicated in a task of discrimination of two natural syllables (/ba/ vs. /ga/) matched for prevoicing and overall duration. Two sets of 1,600 RTs were again collected from observer S.D. Both sets showed a significant oscillation (respectively, 43.0 Hz, $p < .002$; 46.9 Hz, $p = .024$). The 20-Hz through 100-Hz components of the two histograms showed a shifted oscillatory cross-correlogram and were negatively correlated at lag 0, $r = -.439$, $t(254) = 7.80$, $p < 10^{-6}$, again concurrent with a decrease in median RT from 294 ms to 287 ms. Further research should assess more systematically the variations with training of cycle phase, cycle duration, and mean number of cycles before responding.

CONCLUSION

In the present study, a fine-grained periodic structure was found within re-

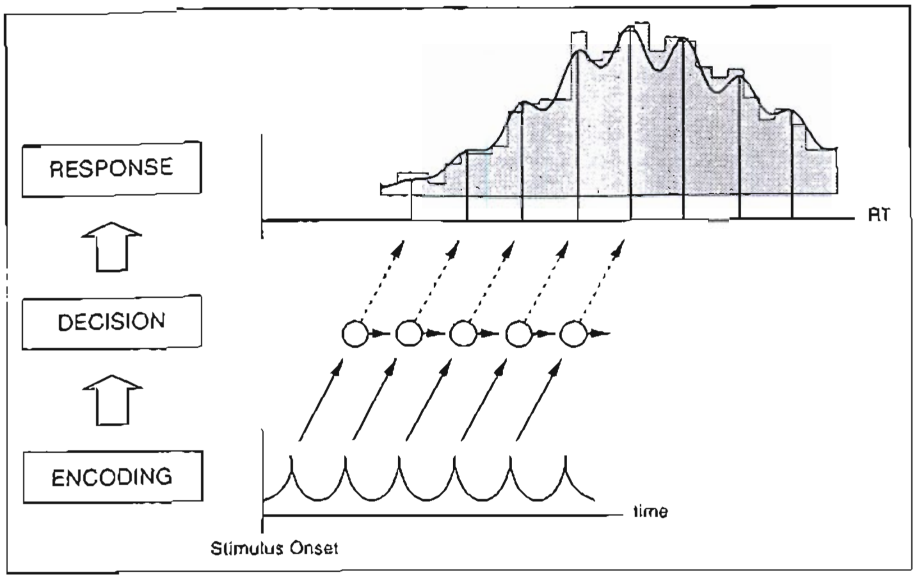

Fig. 3. Possible model for RT oscillations. Perceptual information is transmitted in packets at regular moments in time. For each discrete packet of information, a decision is taken either to respond immediately or to check with the next packet. The number of cycles before responding varies stochastically from trial to trial, generating a multimodal RT distribution. The 6-ms histogram from observer S.D. in the auditory conjunction task (1,433 correct RTs) is used for illustration. The fitted curve was obtained by minimizing χ^2 from a model with five free parameters, $\chi^2(47) = 46.6$.

action time distributions. The oscillation period was systematically related to task difficulty, and subjects appeared to respond after an approximately constant number of cycles regardless of the task. These lawful psychological phenomena have potential significance for cognitive studies of sensory and decision processes. Stimulus-induced oscillations have also been observed in the neuronal or brain electrical activity of several species, including humans (Galambos et al., 1981; Pantev et al., 1991; Ribary et al., 1991). These oscillations could provide a biological basis for the results presented here. At odds with the present results, however, is the finding that neuronal oscillations are often highly variable and not phase locked to the stimulus (Eckhorn et al., 1988; Gray & Singer, 1989; Gray, Engel, König, & Singer, 1992). This may be related to the fact that in neurobiological studies, the animals are generally anesthetized, or awake but passive, and that the stimuli used often do not have a sharp onset. Although the assumption of a common mechanism for temporal oscillations in the psychological and neurobiological domains is tempting, it remains to be convincingly established.

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